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ABSTRACT

It appears that a railgun can be used to accelerate an impactor plate to velocities of 10 to 40 km/s, which could generate shock pressures of 1 to 10 TPa. As a first step to determining the potential and limits of railgun accelerators for shock-wave equation-of-state research, a joint team of scientists and engineers at Los Alamos National Laboratory and Lawrence Livermore National Laboratory have initiated railgun research. We have utilized a combined capacitor bank and magnetic flux compression generator to power railguns and have demonstrated the feasibility of accelerating projectiles to ~10 km/s. This paper reports the status of experimental research directed toward launching EOS impactors and achieving higher velocities.

INTRODUCTION

Equation-of-state (EOS) research with shock waves can benefit from two important features of railgun-launched projectiles: high velocity (greater than 10 km/s) and large impactors (1-cm diam by 1-mm thick or larger). Impact velocities of 10 to 40 km/s would result in shock pressures of about 1 to 10 TPa for a tungsten impactor and target. The railgun's ability to accelerate large projectiles will permit fabrication of precision targets and impactors with ordinary machine tools and the use of well-developed diagnostic techniques currently used with two-stage light gas gun and explosive-accelerated impactors. Below we briefly describe the operation of railguns, launcher requirements for EOS research, and the joint Los Alamos National Laboratory and Lawrence Livermore National Laboratory railgun development project.

PRINCIPLE OF OPERATION

The railgun consists of a pair of rigid parallel conductors that carry current to and from an interconnecting movable conductor which functions as an armature (see Fig. 1). The force F on the armature is given by

$$F = \frac{L' I^2}{2} , \tag{1}$$

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where I is the armature and rail current and L' is the inductance per unit length of the rail pair. A plasma arc serves as the armature. Confinement of the plasma arc behind the projectile is provided by the conducting rails on two sides and dielectric rail spacers on the other two sides. For EOS research the impactor is mounted in a sabot to maintain alignment and plasma confinement during acceleration. A variety of power sources can provide the megampere current and millisecond pulse durations needed.
In the past, railguns have been powered by battery,[1] capacitor bank,[2] homopolar generator,[3] and magnetic flux compression generator (FCG).[4,5]

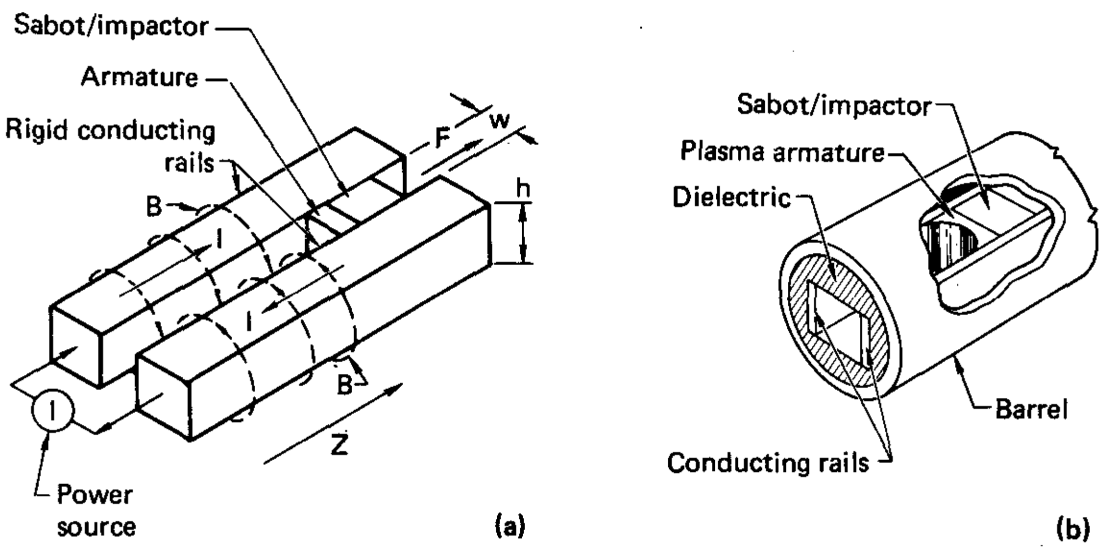

Fig. 1. (a) A railgun accelerator utilizes a power source that supplies the current to generate a magnetic field which, in combination with the armature current, exerts a propulsive force on the backside of the sabot containing the impactor. (b) Cutaway of railgun assembly. The dielectric maintains the rail position and, along with the rails, confines the plasma behind the sabot.

In a drag-free railgun, the projectile momentum is

$$mv = \frac{L'}{2} \int I^2 dt \ , \qquad (2)$$

where m is the projectile mass, v is the velocity, and t is time. A typical value of L' is about 0.4 μH/m. Hence, 1 MA delivered to a railgun for 1 ms would impart a momentum of 200 N•s (i.e., a 5-g projectile at a velocity of 40 km/s).

REQUIREMENTS FOR AN EOS LAUNCHER

To provide a significant advantage over contemporary shock-wave generation techniques, a railgun must meet a set of requirements that can be summarized as (1) launch velocities in the range of

10 to 40 km/s; (2) impactor size of 10-mm diam by 1-mm thick; (3) impactor flatness sufficient to limit shock velocity measurement uncertainty to 1%; and (4) impactor tilt of less than 1 or 2 degrees.[6] Furthermore, operation of the launcher must not interfere with EOS data acquisition and, in the long run, it is desirable that the cost of maintaining and operating the launcher be comparable to the cost of the EOS experiments.

LAUNCH VELOCITY

Lexan polycarbonate projectiles have been launched intact at velocities up to ~6 km/s and accelerated to velocities of about 10 km/s.[1,7] The operation of railguns has been well enough understood to develop a model[8] which indicates that velocities in the 10 to 40 km/s range might be possible.[9]

IMPACTOR AND SABOT MASS

The mass of a 10-mm-diam by 1-mm-thick impactor will range from 0.145 g for beryllium to 1.51 g for tungsten. A sabot is required to keep the impactor in alignment during acceleration, to electrically insulate the impactor from the rails to prevent current flow through it, and to confine the plasma to its base. A solid 12-mm polycarbonate sabot with an aspect ratio of 2/3 would have a mass of 1.39 g for a square-bore gun and 1.09 g for a round-bore gun. The tungsten impactor and square-bore Lexan sabot result in a total mass of 2.9 g and would have a kinetic energy of 2.3 MJ at 40 km/s.

IMPACTOR FLATNESS AND TILT

In order to limit the uncertainty Δu_s in shock velocity u_s, the uncorrected[10] impact distortion ε must be

$$\varepsilon \leq b \left(\frac{v}{u_s}\right)\left(\frac{\Delta u_s}{u_s}\right) , \qquad (3)$$

where b is the thickness of the target. For a 1-mm-thick tungsten impactor impacting a 3-mm-thick tungsten target at 40 km/s, ε must be ±0.04 mm or less in order to limit $\Delta u_s/u_s$ to 1%. Limiting the impactor tilt must be accomplished with sabot and launcher design and precision, particularly at the muzzle of the railgun.

JOINT LOS ALAMOS/LIVERMORE RAILGUN R&D PROJECT

Los Alamos and Livermore are jointly developing railguns for application to EOS research. Experiments at Los Alamos use a 940-kJ (3 mf, 25 kV) capacitor bank coupled with explosively driven FCGs to power railguns[5] designed and fabricated at both Los Alamos and Livermore[11] (see Fig. 2). Experiments at Livermore use a 375-kJ (30 mf, 5 kV) capacitor bank as a power source. The capacitor banks

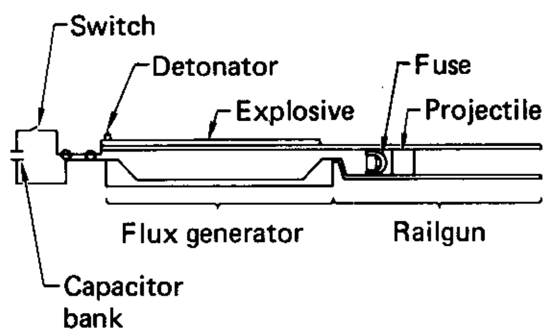

Fig. 2. Components of the FCG-railgun system. The capacitor-bank discharge develops a current in the inductance of the FCG. After the FCG is charged, the detonator ignites the explosive that drives the top conductor toward the bottom one. At this time, the circuit is shorted at the input end of the FCG, trapping the magnetic flux in the FCG-railgun system. Continued implosion of the FCG drives the flux into the railgun and maintains an extended near-constant current pulse in the railgun.

alone can generate railgun currents of about 1 MA. The FCG system can supply inputs ranging from nearly constant megampere currents for about 0.5 ms to shorter duration peak currents of several megamperes. The full-scale, high-energy experiments are done with FCG's (see Table I), while a capacitor bank alone is used for experimentation with similar peak currents, albeit shorter pulse duration.

TABLE I. Summary of results of FCG-powered 12.7-mm-bore railgun experiments.[7]

Accelerator length (m)	0.9	1.8	1.8
Projectile mass (g)	2.9	3.1	3.1
Initial capacitor bank energy (kJ)	70	200	390
Peak current (MA)	0.6	0.8	1.2
Peak acceleration (10^6 "g's")	1.9	3.2	7
Peak stress/elastic limit	5	9	15
Launch velocity (km/s)	2.8	5.5	~10
Projectile integrity verified	Yes	Yes	No

We have commenced an effort to launch saboted impactors and implement the use of shielded shorting pins (see Fig. 3). Flatness and tilt measurements will be made in the near future. Sabot design modifications will then be made to reduce tilt and irregularities of the impact if required. Higher energy experiments are expected to achieve higher launch velocities.

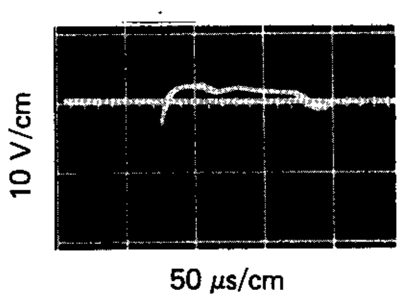

Fig. 3. Pin signal generated by a 1-km/s impact of a 1-g Lexan projectile with an aluminum target.

CONCLUSIONS

In summary, the requirements for a useful EOS railgun launcher are well-defined. The railgun and power supply performance characteristics are fairly well understood up to 10 km/s. We conclude that railguns have the potential to accelerate and launch large impactors at velocities in the 10 to 40 km/s range. The principal areas needing development are (1) techniques to minimize railgun interference with shock-wave diagnostics and (2) the attainment of velocities greater than 10 km/s with flat impacts.

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